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Heat transfer characteristics of nanofluids in heat pipes: A review

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ABSTRACT

Extensive research work on heat transfer in heat pipe using conventional working fluids has been carried out over the past decade. Heat transfer in heat pipes using suspensions of nano meter–sized solid particles in base liquids have been investigated in recent years by various researchers across the world for finding new opportunities. The suspended nanoparticles effectively enhance the transport properties and heat transfer characteristics of base fluids in heat pipes. The study reveals an improvement in the thermal efficiency and reduction in the thermal resistance of heat pipe with nanofluids, than that of conventional working fluids. This paper reviews and summarizes recent research on fluid flow and the heat transfer characteristics of nanofluids in heat pipes and identifies perspective of nanofluids that can be used in heat pipes for further research.

Contents

1. Introduction

Heat removal is an important parameter while designing compact electronic components. Initially copper heat sinks were used to remove the heat from the mother board of desktop computers. Nowadays, to increase the heat transfer in electronic components, like laptops, note book computers etc., heat pipes have been used. Heat pipe is a device used to transfer the heat from one place to the other. The heat pipe consists of evaporator section, adiabatic section and condenser section (Fig. 1). Heat absorption takes place in the evaporator section and heat rejection at the condenser section. Adiabatic section is fully insulated. The heat pipe is evacuated using a vacuum pump and is filled up with the working fluid. The working fluid absorbs the heat at one end of the heat pipe called evaporator and releases the heat at the other end called condenser. Due to the capillary action, the condensed working fluid through the mesh wick structure returns

Abbreviations: SS, Single-step process; FHP, Flat heat pipe; GHP, Grooved heat pipe; OHP, Oscillating heat pipe; EG, Ethylene glycol; DI, De-ionized; CTAB, Cetyl trimethyl ammonium bromide; SDS, Sodium dodecyl sulfate; ppm, Parts per million; NTU, Number of transfer units; HFC, Hydro fluro carbon; CHF, Critical heat flux; CFD, Computational fluid dynamics; TPCT, Two-phase closed thermosyphon; HTC, Heat transfer coefficient; TEM, Transmission electron microscope; SEM, Scanning electron microscope; OD, Outer diameter; L, Length

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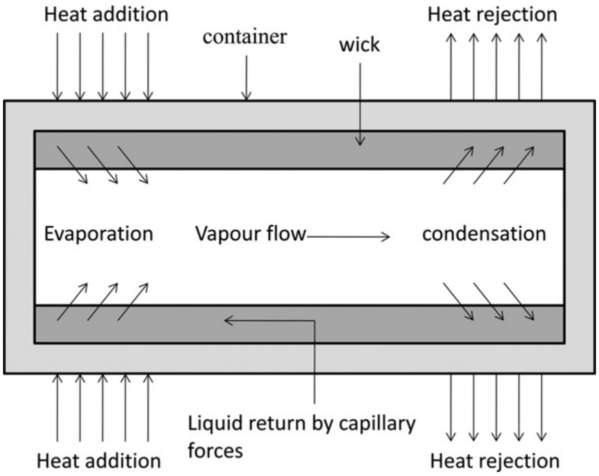


Fig. 1. Schematic diagram of heat pipe.

Table 1
Thermal conductivities of various solids and liquids.

Material	Thermal conductivity (W/m-K)
Metallic solids copper	401
Aluminum	237
Nonmetallic solids silicon	148
Alumina (Al_2O_3)	40
Metallic liquids sodium (644 K)	72.3
Nonmetallic liquids water	0.613
Ethylene glycol (EG)	0.253
Engine oil (EO)	0.145

to the evaporator, on the inside wall of the pipe. Normally conventional fluids are used in heat pipes to remove the heat. Nowadays, nanofluids play an important role in heat pipes to increase the heat transfer compared to conventional fluids. Thermal conductivity is an important parameter in enhancing the heat transfer performance of a heat transfer fluid. Researchers have also tried to increase the thermal conductivity of base fluids by suspending nanometer-sized solid particles in fluids since the thermal conductivity of solid is typically higher than that of liquids, as seen from Table 1. Many researchers have presented the heat transfer characteristics of heat pipe using nanofluids.

The nano meter sized particles have great potential in improving heat transfer of base fluids. The properties of nano particle of size lesser than 100 nm are different from conventional fluids and result show that there is an improvement in heat transfer [1–3]. Xuan and Li [4] have studied the thermal conductivity and convective heat transfer of nanomaterials as substitutes to water and ethylene glycol. Lin et al. [5] have presented the experimental results of a two-phase heat transfer of R141b refrigerant in a 1 mm diameter tube. Lin et al. [6] have developed a miniature heat pipe for heat removal of high heat flux electronics devices. Thermal performance of a solar cooking system using vacuum tube collectors with heat pipes and a refrigerant as working fluid has been experimentally investigated by Esen [7]. Song et al. [8] have experimentally investigated the heat transfer performance of axially rotating heat pipes by the effects of the rotational speed, heat pipe geometry, and working fluid loading under steady state. Xuan et al. [9] have investigated the effects of the different heat fluxes, orientations and amount of the working fluid on the performance of a flat plate heat pipe. Wen and Ding [10] have experimentally investigated the convective heat transfer of nanofluids in a copper tube at the entrance region under laminar flow conditions. Zhou [11] has investigated the improvement in heat transfer characteristics of copper nanofluids with and without acoustic cavitations. Bang and Chang [12] have studied the boiling heat transfer characteristics of water with Al_2O_3 nanoparticles suspended by the effects of different volume concentrations of nanoparticles. The application of heat pipes in modern heat exchangers and the micro and miniature heat pipes used in cooling of electronic components has been studied [13,14]. Huang et al. [15,16] have evaluated the performance of a heat pipe in the solar-assisted heat pump water heater system. Lin et al. [17] have simulated numerically a heat pipe heat exchangers integrated with the dehumidification process. Koo and Kleinstreuer [18] have proposed the steady laminar flow of liquid nanofluids in micro channels. Liu et al. [19] have experimentally investigated the effects of thermal conductivity of nanofluids, ethylene glycol and synthetic engine oil on the multiwall carbon nanotubes. The convective heat transfer coefficient of nanofluids has been investigated under laminar flow in a horizontal tube heat exchanger by Yang et al. [20]. Zeinali Heris et al. [21] investigated the circular tube with the laminar flow convective heat transfer of oxide nanofluids under constant wall temperature boundary condition. Jang and Choi [22] have numerically investigated the heat transfer characteristics of micro channel of heat sink with nanofluids.

Li et al. [23] have proposed the study of the heat and mass transfer properties of HFC134a gas hydrate in nano-copper suspension. Palm et al. [24] have numerically investigated a typical radial flow cooling system, an improvement in heat transfer characteristics of coolants with suspended metallic nanoparticles. Kang et al. [25] have experimentally investigated on the heat transfer characteristics of heat pipe with silver nanofluid. Ding et al. [26] have proposed a study on the heat transfer characteristics of aqueous suspensions of carbon nanotubes in pressure-driven laminar pipe flows of nanofluids. The effects of the length of the evaporator and vapor temperature on the critical values of the upper and lower boundaries of loop heat pipe were considered by Liu et al. [27]. Vlassov et al. [28] have investigated the characteristics of a heat pipe radiator assembly for space application filled with ammonia or acetone. He et al. [29] have conducted study on the heat transfer and flow characteristics of aqueous suspensions of TiO_2 nanoparticles flowing upward through a vertical pipe. Nguyen et al. [30] have experimentally investigated the heat transfer enhancement of an Al_2O_3–water nanofluid for cooling of electronic components. Trisaksri and

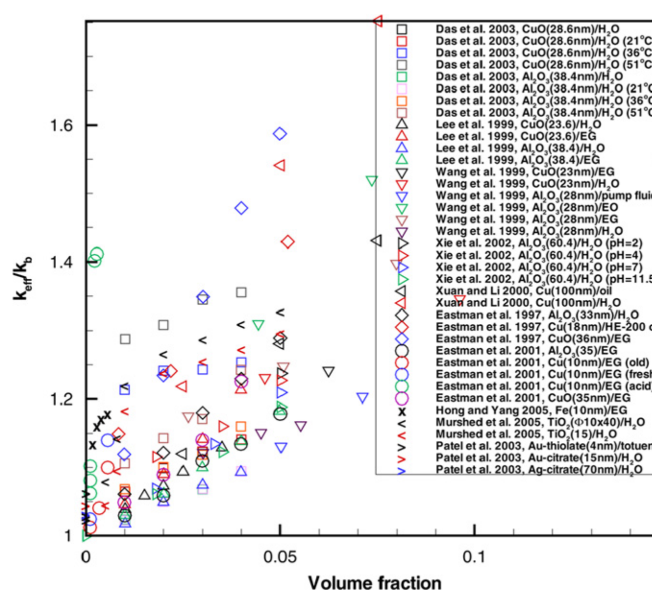


Fig. 2. Comparison of experimental data on thermal conductivity of nanofluids [34].

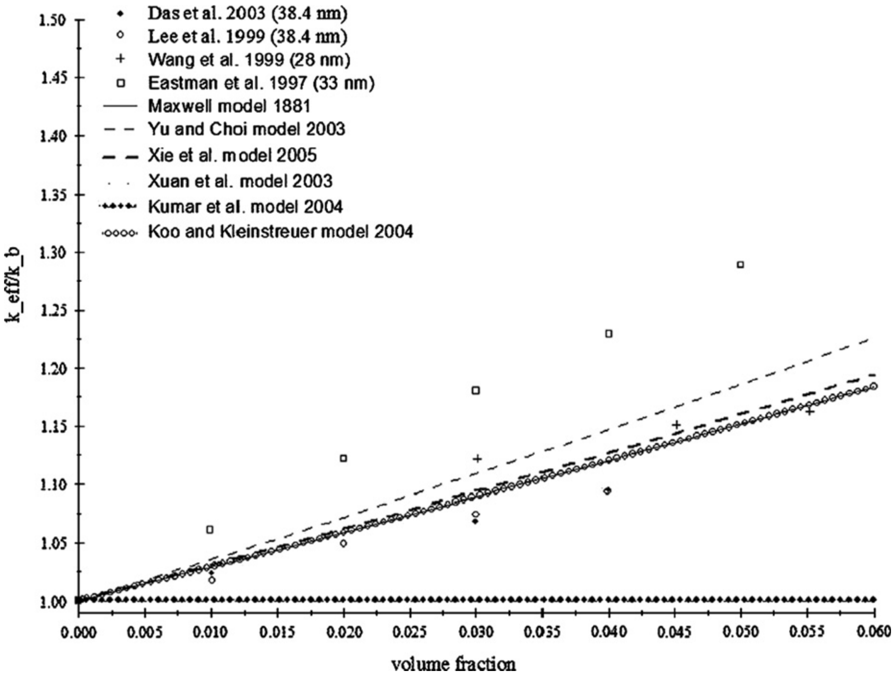


Fig. 3. Comparison between selected theoretical models and experimental data on thermal conductivity for Al_2O_3/water nanofluids. [34].

Wongwises [31] summarized the recent developments in research on the heat transfer characteristics of nano fluids. The presence of suspended nanoparticles enhances the heat transfer characteristics of conventional fluids. Chein and Chuang [32] have studied the micro channel heat sink performance using nanofluids and compared the theoretical results with the measured data. Mansour et al. [33] have found the effect of uncertainties in physical properties on forced convection heat transfer with nanofluids. Wang and Mujumdar [34] summarized the recent investigations on nanofluids and recent research on fluid flow and heat transfer characteristics of nanofluids in forced and free convection flows. In this, researchers have given much attention on thermal conductivity rather than heat transfer characteristics. Fig. 2 shows the effect of volume fraction on thermal conductivity of nanofluids. The findings of many researchers were compared and CuO of 36 nm size nanoparticles with base fluid ethylene glycol, having a thermal conductivity higher than other nanoparticles dispersion, was selected.

The effects of volume fraction on thermal conductivity of nanofluids were compared between theoretical models and experimental data for Al_2O_3/water nanofluids (Fig. 3). The effect of the size and shape of the nanoparticles, the interfacial contact resistance between nanoparticles and base fluids, the temperature dependence or the effect of Brownion motion, and the effect of clustering of particles are factors considered for the future research to find the effective thermal conductivity of nanofluids in depth.

In general, the heat transport property of heat transfer devices is limited by the working fluid. The heat transfer enhancement of heat transfer devices is only possible by adding additives to the working fluids. The use of nanofluids is proposed, to increase the thermal performance of heat transfer devices. The papers presented on the study of heat transfer and flow characteristics of the heat pipe with nanofluids have rarely been reported. No review reported on the thermal performance of the heat pipe with nanofluids. The objective of this paper is to present an overview of literature dealing with recent developments in the study of heat transfer using nanofluids in heat pipes and some important inferences from the various papers are also highlighted.

2. Preparation of nanofluids

Nano fluids preparation is the preliminary step in experiential studies. The essential requirements for the nanofluids are, it should be even, stable suspension, adequate durability, negligible agglomeration of particulates, no chemicals change of the particulates or fluid, etc., Nano fluids can be prepared by dispersing nanometer scale solid particles into base fluids such as water, ethylene glycol, oil etc., In the synthesis of nano fluids, agglomeration is major problem. The single step and two step methods are used to produce nano fluids. The summary of results reported by various researchers in the area of nanofluid preparation is provided in Table 2.

2.1. The single-step process

Nano materials and nano suspension are produced by various methods. A good overview of synthesis method was provided by Gleiter [35]. Initially oxide particles were tried for nanofluids, because they were easy to produce and chemically stable in solution.Al_2O_3 and CuO nanopowder were produced by various investigators through inert gas condensation process [1,36] that produced 2–200 nm sized particles. The major problem with this method is its tendency to agglomerate and its unsuitability to produce pure metallic nanopowder. But it can overcome the agglomeration by using a direct evaporation condensation method. The two method process is a modification of the inert gas condensation process that has been adopted at Argonne national laboratory, USA [37]. The limitation of this method is low vapor—pressure fluids and oxidation of pure metals but it provides excellent control over particle size and produces particles for stable nanofluids without electrostatic stabilizers.

The single-step direct evaporation approach was developed by Akoh et al. [38] and this technique is called as vacuum evaporation onto a running oil substrate. The original idea of this technique was to produce nanoparticles, but it was difficult to subsequently separate the particles from the fluids to produce dry nanoparticles. An advantage of this method is that the nanoparticles agglomeration is minimized while the disadvantage is only

Table 2
Summary of nanofluid preparation methods.

Authors	Method	Nano fluids/size (nm)	Observations
Eastman et al. [37]	SS—direct evaporation condensation	Cu-EG/ < 10 nm	Excellent control over particle size and stable nanofluids without surfactant
Choi [36] Lee [41]	SS—inert gas condensation & two-step method	Al_2O_3,CuO/2–200 nm	Unsuitable to produce pure metallic nanopowders and its tendency to form agglomerates
Xuan et al. [4]	Two-step method	Transformer oil–Cu, water–Cu /100 nm	To enhance the stability of nanofluid, salt and oleic acid as dispersant are added
Gleiter [35]	SS—synthesis methods & two-step method	–	Initially metal particles were easy to produce and chemically stable
Wang et al. [1]	Two-step method	Al_2O_3,CuO–water, EO, EG	To disperse the particles and to reduce the agglomeration of particles ultrasonic equipment is used
Akoh et al. [38]	SS—vacuum evaporation onto a running oil substrate technique	Fe_3O_4	Difficult to separate the particles from the fluids to produce dry nanoparticles
Eastman et al. [41]	SS—modified vacuum evaporation onto oil technique	Al_2O_3	Cu vapor is directly condensed into nanoparticles by contact with a flowing low-vapor-pressure liquid ethylene glycol
Zhu et al. [39]	SS—novel one-step chemical method	Cu	The reaction rate and properties of Cu nanofluids affected by the addition of $NaH_2PO_2 \cdot H_2O$ and the adoption of microwave irradiation
Lo et al. [40]	SS—vacuum-based submerged arc nanoparticle synthesis system	CuO, Cu_2O, Cu with different dielectric liquids	Agglomeration is minimized, low vapor pressure fluids are compatible with a process
Murshed et al. [42]	Two-step method	TiO_2–water/15 nm	To ensure better stability and proper dispersion of TiO_2–water nanofluids, surfactants like Oleic acid and cetyl trimethyl ammonium bromide (CTAB) were used

SS—single-step process.

low vapor pressure fluids are compatible with such process. A novel one-step chemical method for preparing copper nanofluids by reducing $CuSO_4 \cdot 5H_2O$ with $NaH_2PO_2 \cdot H_2O$ in ethylene glycol under microwave irradiation is presented by Zhu et al. [39]. Results showed that additions of $NaH_2PO_2 \cdot H_2O$ and adoption of microwave irradiation are two significant factors which affect the reaction rate and properties of cu nanofluids. Lo et al. [40] developed a vacuum-based submerged arc nanoparticles synthesis system to prepare CuO, Cu_2O and Cu based nanofluids with different dielectric liquids. The morphologies of nanoparticles depended on the thermal conductivity of dielectric fluids.

2.2. The two step process

This method is extensively used in the synthesis of nanofluids considering the availability of nanopowders supplied by various companies. In this method nano particles were produced first and then dispersed in base fluids.

The dispersion of particles is produced by ultrasonic equipment and it reduces the agglomeration of particles also. For example, Lee et al. [41], and Wang et al. [1] used this method to produce Al_2O_3 nanofluids. Also, TiO_2 suspension in water using the two step-method was prepared by Murshed et al. [42]. Some nanoparticles reported in the literature are gold (Au), silver (Ag), silica and carbon nanotubes. As compared to the single-step method, this technique works well for oxide nanoparticles, while it is less successful with metallic particles. Other than the use of ultrasonic equipment, some other methods such as control of pH or addition of surface active agents are also used to attain stability of the suspension of the nanofluids against sedimentation. The surface properties of the suspended particles are changed by this method and it suppresses the tendency to form particles clusters. It should be noted that the selection of surfactants should depend mainly on the particles and properties of the solutions.

For instance, salt and oleic acid as dispersants are known to enhance the stability of transformer oil–Cu and water–Cu nanofluids, respectively [4]. Murshed et al. [42] used oleic acid and cetyl trimethyl ammonium bromide (CTAB) surfactants to ensure proper dispersion and better stability of TiO_2-water nanofluids. Hwang et al. [43] used sodium dodecyl sulfate (SDS) during the preparation of water-based multiwall carbon nanotube dispersed nanofluids, since the fibers are entangled in the aqueous suspension. However, the heat transfer performance of the nanofluids can be affected by the addition of dispersions in fluids, especially at high temperature i.e., in the convective heat transfer and two-phase heat transfer regime.

Table 3
Volumes of materials used in different synthesis conditions [47].

Condition	Na_3 citrate (ml)	Tannic acid (ml)	$HAuCl_4$ (ml)
A	0.2	2.5	3
B	0.2	5	6
C	3	0.1	1
E	3	2.5	6
G	3	0.1	3

3. Heat transfer characteristics of nanofluids in heat pipes

3.1. Experimental investigations

Many researchers have reported experimental studies on the thermal conductivity of nanofluids in heat pipes, thermal resistance and thermal efficiency of heat pipe. A derivation of Fourier's law and temperature data were used to calculate the thermal conductivity. The heat pipe thermal efficiency can be calculated from the ratio of cooling capacity rate of water at the condenser section and supplied power at the evaporator section. The results from all the available experimental studies indicated that nanofluids containing a small amount of nanoparticles have substantially higher thermal conductivity than those of base fluids and also there is an increase in the thermal efficiency of heat pipe (Table 4).

Naphon et al. [44] investigated the enhancement of heat pipe thermal efficiency with TiO_2+alcohol nanofluids. The test section is fabricated from the straight copper tube with the outer diameter 15 mm and length 600 mm. In this, working fluids of heat pipe such as de-ionized water, alcohol, and nanofluids (alcohol and TiO_2 nanoparticles) are tested. The diameter of

Table 4
Summary of experimental studies on nanofluids in heat pipes.

Researcher	Type/size of heat pipe	Working fluid (nanoparticle size)	Effect
Paisarn Naphon et al. [44]	Straight copper tube/O.D.—15 mm, L-600 mm	TiO_2–water,TiO_2–alcohol (21 nm)	[a]
Tsai et al. [45]	Circular heat pipe /O.D.—6 mm, L-170 mm	Au–water (21.3, 43.7, 8, 9.3, 15.6 nm)	[a]
Yu-Tang Chen [46]	O.D.—3 mm, L-200 mm	Ag–water (35 nm)	[a]
Han et al. [47]	Grooved heat pipe (GHP)/O.D.—12 mm, L-500 mm	Hybrid nanofluids Ag–water & Al_2O_3–water (27 nm &89 nm)	[b]
Shung-Wen Kang et al. [48]	Grooved circular heat pipe /size 211 μm wide × 217 μm	Ag–water (35 nm)	[a]
Ji et al. [49]	Oscillating heat pipe (OHP)/O.D.—3.18 mm, L-155 mm	Al_2O_3–EG & water (9, 40, 60 & 80 nm)	[a]
M.G. Mousa [50]	Circular heat pipe	Al_2O_3–water (40 nm)	[a]
Kyu Hyung Do et al. [51]	Circular screen mesh wick heat pipes/ O.D.—4 mm, L-300 mm	Al_2O_3–water (30 ± 5 nm)	[a]
Xue et al. [52]	Thermosyphon/L-350 mm	SiO_2–water (30 nm)	[b]
Asghar et al. [53]	Thermosyphon/O.D.—19 cm, L-100 cm	–	[a]
Suresh et al. [54]	Straight copper tube/O.D.—12 mm, L-1000 mm	Al_2O_3–water (15 nm)	[a]
Gabriela et al. [56,57]	Thermosyphon/O.D.—15 mm, L-2000 mm	Iron oxide–water (4–5 nm)	[a]
Ji et al. [58]	Oscillating heat pipe (OHP)/O.D.—3.18 mm, L-155 mm	Al_2O_3–water (50 nm, 80 nm, 2.2 μm, 20 μm)	[a]
Qu et al. [60]	Oscillating heat pipe (OHP)/O.D.—3 mm, L-225 mm	SiO_2–water, Al_2O_3–water (30 nm, 56 nm)	Al_2O_3 –water[a] SiO_2-water[b]
Putra et al. [61]	Straight copper tube/O.D.—8 mm, L-200 mm	Al_2O_3–water, Al_2O_3–EG, TiO_2–water, TiO_2–EG, ZnO–EG	Al_2O_3 –water[a]
Brusly Solomon et al. [63]	Straight copper tube/O.D.—19.5 mm, L-400 mm	Cu – water(80-90 nm)	[a]
Yang et al. [64]	Loop thermosyphon/O.D.—16 mm, L-600 mm	CuO-water(50 nm)	[a]
Rasari Saleh et al. [65] (2012)	Straight copper tube/O.D.—8 mm, L-200 mm	ZnO-EG(18,23 nm)	[a]
Adi. T. Utomo et al. [67]	Stainless steel tube	Al_2O_3–water, TiO_2–water(50-60 nm,20-30 nm)	[a]
Dey et al. [68]	Screen mesh wick heat pipe/O.D.—10 mm, L-300 mm	Cu – water(≈ 40 nm)	[a]
Senthil Kumar et al. [70]	Straight copper tube/O.D.—20 mm, L-600 mm	Cu – water(40 nm)	[a]

[a] Thermal performance enhancement.
[b] Thermal performance reduction.

Table 5
Summary of theoretical studies on nanofluids in heat pipes.

Authors	Nanofluids	Comments
Shafahi et al. [71]	Al_2O_3, CuO, TiO_2	Nanoparticles decrease the thermal resistance and an increase in the maximum heat load capacity of the flat-shaped heat pipe
Tahery et al. [72]	Al_2O_3	The vertical cavities in nanofluids, had better efficiency in natural convection numerical modeling for both horizontal and vertical fluid layer
Vasu et al. [73]	Al_2O_3	Cooling capacity of Al_2O_3 -water nanofluid is very high
Murugesan [74]	Al_2O_3 CuO TiO_2	The particle shape, Brownian motion and nanolayer are significant in enhancing the thermal conductivity of nanofluids
Do, and Pil Jang [75]	Al_2O_3	The thermal performance is enhancing up to 100% although water-based Al_2O_3 nanofluids with the concentration less than 1.0% is used as working fluid. -the thermal resistance of the nanofluid heat pipe tends to decrease with increasing the nanoparticles size
Maryam et al. [76]	Al_2O_3 CuO TiO_2	The thermal resistance decreases with increase in concentrations An optimum mass concentration and smaller particle in size providing the highest thermal performance

TiO_2 nanoparticles with 21 nm are used, in which the mixtures of alcohol and nanoparticles are prepared using an ultrasonic homogenizer. The parameters considered are the effects of percentage charge amount of working fluid, percentage nanoparticles volume concentrations, and heat pipe tilt angle on the thermal efficiency of heat pipe. The nanoparticles added with the base fluid have a significant effect on the enhancement of thermal efficiency of heat pipe. The variation of heat pipe thermal efficiency with heat pipe tilt angle at 66% charge amount of de-ionic water and alcohol have been calculated. Because of the gravitational force of working fluid, the heat pipe efficiency increases with increasing tilt angle. Due to higher onset of liquid film on the inner wall in the condenser section and because of increase in thermal resistance, the heat pipe thermal efficiency decreases as heat pipe tilt angle greater than 60° for de-ionic water and greater than 45° for alcohol. The variation of heat pipe thermal efficiency with heat flux at heat pipe tilt angle of 60° for various percentage charge amount of de-ionic water was calculated. The absorption heat capacity depends on the charge amount of working fluid and more space for the vapor of working fluid. Due to that, the heat pipe thermal efficiency increases with increasing charge amount of working fluid. Maximum heat pipe thermal efficiency is attained at the optimum condition of 45° tilt angle and 66% charge amount of alcohol. The thermal efficiency of

heat pipe is 10.60% higher than the base working fluid, with 0.10% nanoparticles volume concentration (Fig. 4).

Tsai et al. [45] reported an effect of structural character of gold nanoparticles in nanofluid on heat pipe thermal performance. The circular heat pipe is made of copper with a length of 170 mm and an outer diameter of 6 mm. A 200 mesh wire screen is used in heat pipe. Gold nanoparticles of different sizes were prepared by reduction of aqueous hydrogen tetrachloroaurate ($HAuCl_4$, Aldrich Chemical) with trisodium citrate and tannic acid (Aldrich Chemical). In this study, the size of gold nanoparticles was adjusted by changing the amounts of tetrachloroaurate, trisodium citrate and tannic acid (Fig. 5). The thermal resistance of circular heat pipe ranges from 0.17 to 0.215 °C/W with different nanoparticles solutions as shown in Fig. 6. The thermal resistance of heat pipe is 37% lower than that using DI water by condition A. The measured thermal resistance are lower than that of DI water, and the percentage reduction thermal resistance of heat pipe is 25% (by condition C), 23% (by condition D) and 20% (by condition E) (Table 3). The results show that the higher thermal resistance of a vertical circular meshed heat pipe varies with the size of gold nanoparticles.

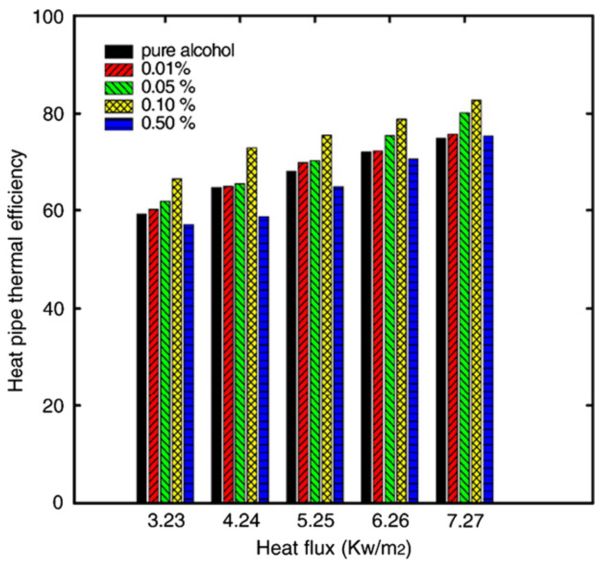


Fig. 4. Variation of heat pipe thermal efficiency with heat flux for different percentage nanoparticles volume concentration [44].

Chen [46] investigated the effect of flat heat pipe thermal performance using silver nano-fluid. The silver nanoparticles of size 35 nm and the pure-water as base working fluid. The heat pipe is fabricated for a thickness of 3 mm and length of 200 cm. Nano-fluid concentrations of 5 mg/l, 50 mg/l and 100 mg/l (ppm) were used. At the same charge volume, the thermal resistance of heat pipe filled nano-fluid was lower than DI water. The reason for enhancement in the thermal performance of FHP by using nano-fluid is higher wettability that enhances the capability and flattens the temperature difference of FHP. The temperature difference and the thermal resistance of FHP with silver nanoparticle solution were lower than that with pure water. The result showed that the silver nano-fluid not only enhanced the thermal performance of traditional circular heat pipes but also increased the thermal performance flat heat pipe. This investigation concluded that the further studies will focus on the effect of the thickness of FHP, nano-fluid concentration and the wettability

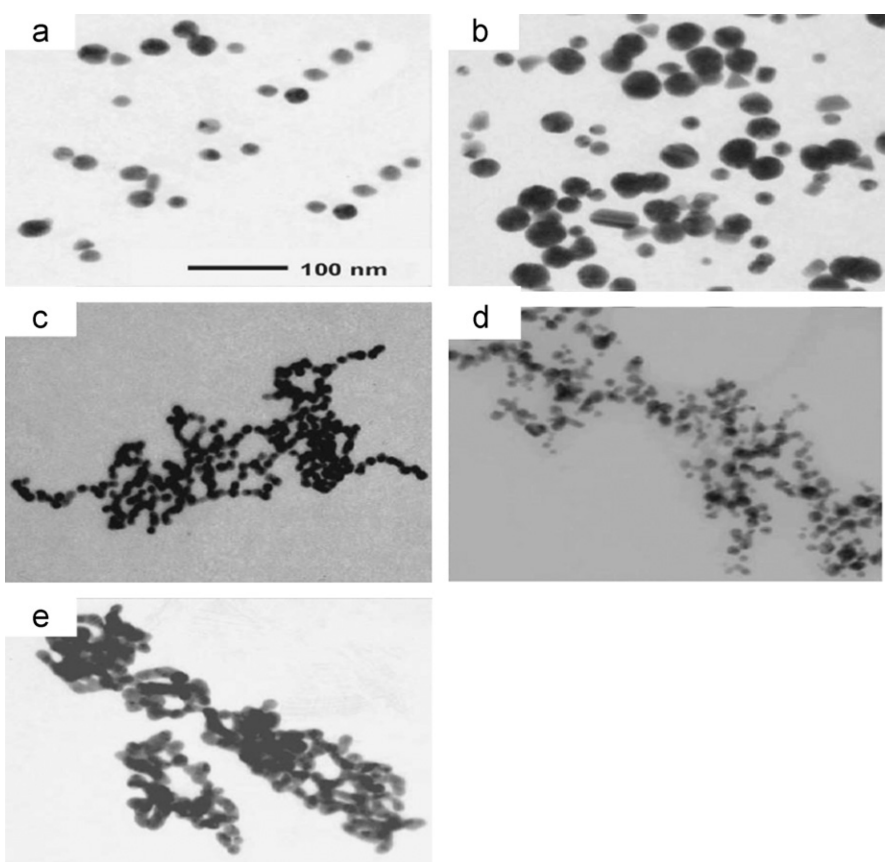


Fig. 5. TEM photographs of gold nanoparticles (magnification of 100,000) [45].

effect of the nano-fluids on various geometry of the heat pipes wick to get the optimum thermal performance of heat pipe.

Han and Rhi [47] investigated the thermal performance of grooved heat pipe (GHP) charged with various nanofluids and hybrid working fluids (Ag–H_2O and Al_2O_3–H_2O) in terms of various parameters such as heat transfer rate, volume concentration, inclination, cooling water temperature, surface state and transient state. The experiment was carried out with 32% of charged amount of working fluid. The nanofluid and hybrid nanofluid shows higher overall thermal resistance with increasing nano particle concentration than the pure water system. The driving parameters which affect the thermal performance of a GHP with nanofluids and hybrid nanofluids were varied. Fig. 7 shows, after the experiment nanofluid was found to be light in color with reduced particle concentration and it was much lighter than nanofluid before experiment. This concluded that the nanoparticles were deposited on the inner surface of GHP. These deposited particles can affect the GHP operation in different ways. The effects of particle deposition are heat transfer performance deterioration and CHF improvement. Comparatively to a vertical position GHP shows better performance at lower angles. This paper presents that nanofluids are not always attractive as a heat transfer fluid for devices with high energy density and also hybrid nanofluids are not much effective compared to the pure nanoparticles nanofluid system. This investigation concluded that the various trails with different combination needed to be studied in future.

Kang et al. [48] investigated the effect of silver nanofluid on heat pipe thermal performance. The grooved circular heat pipe was experimentally tested with DI-water diluted with 10 nm and 35 nm silver particles (Fig. 8), of size 211 μm wide × 217 μm deep. The results showed that at various heat loads, increase in the concentration of nanoparticles dispersion increases the heat pipe wall temperature and also that the thermal resistance of GHP depends on the size of the nanoparticles. The thermal resistance reduction was 50% for 10 nm sized particles and 80% for 35 nm sized particles. The reasons for heat pipe thermal enhancement and thermal resistance are that nano-particles can flatten the transverse temperature gradient of the fluid and reduce the boiling limit because of the increasing effective liquid conductance in heat pipes. This investigation concluded that, further

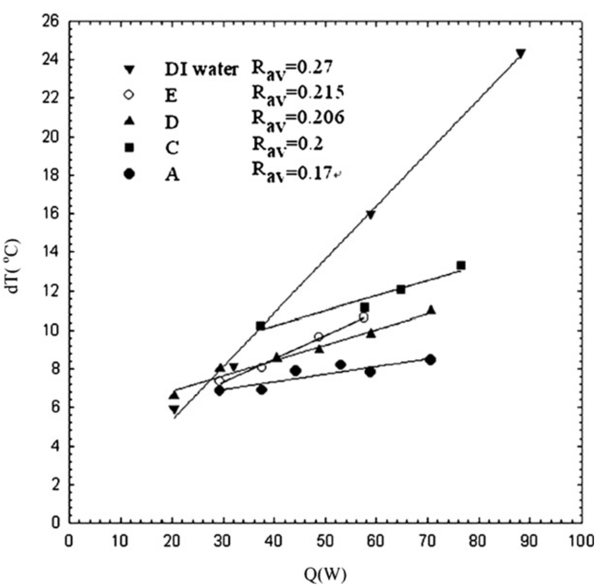


Fig. 6. Measured values of thermal resistance of heat pipe with nanofluids [45].

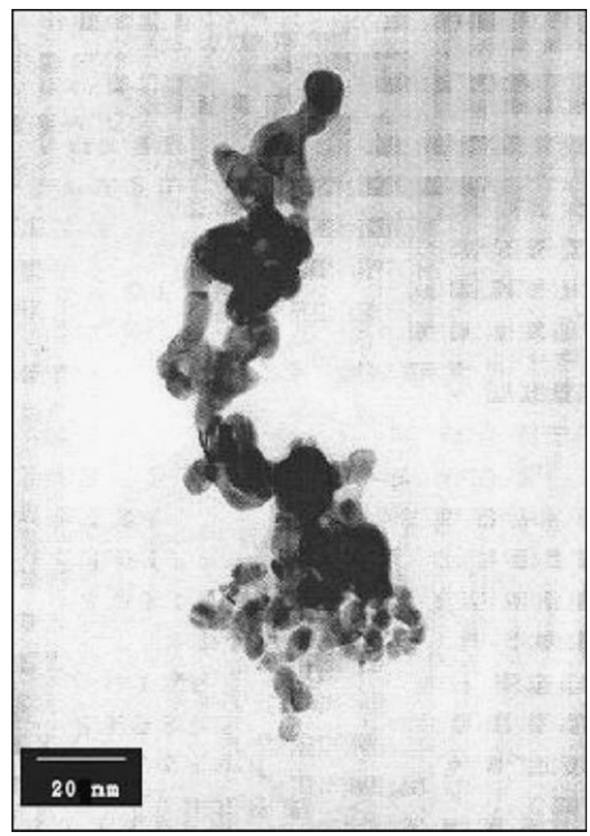


Fig. 8. TEM photographs of Ag nanoparticles (35 nm) [48].

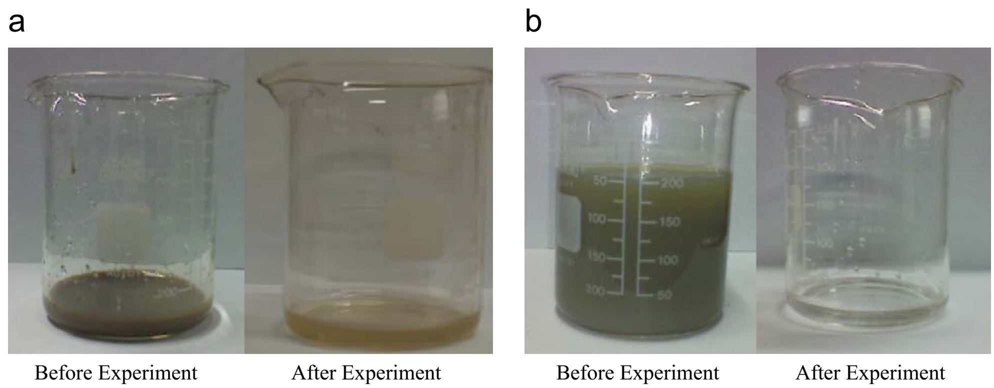
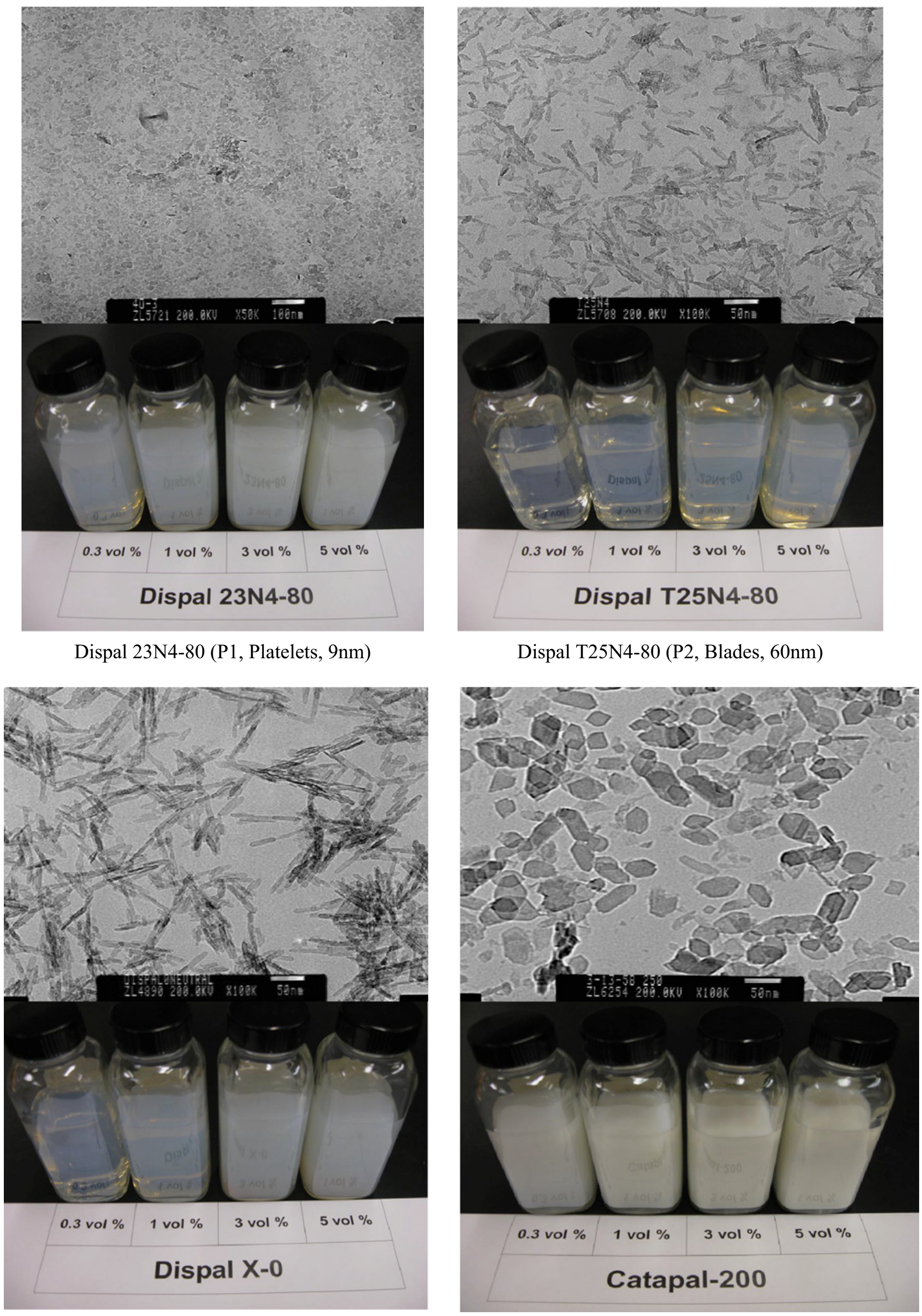


Fig. 7. Nanofluids before and after experiment. [47]. (a) 0.05% Silver+0.1%-Al_2O_3 and (b) Silver 0.05%.

studies on nano-fluid behavior in heat pipes and the properties of nano-fluids must be performed.

Yulong Ji et al. [49] experimentally investigated the alumina nanoparticles shape effect on the heat transfer performance of an OHP. A binary mixture of ethylene glycol (EG) and deionized water (50/50 by volume) was used as the base fluid for the OHP. Four types of nanoparticles with shapes of platelet, blade, cylinder, and brick were studied (Fig. 9). The results showed that the alumina nanoparticles used in the OHP significantly enhance the heat transfer performance and it depends on the particle shape and volume fraction. In the four types, cylinder-like alumina nanoparticles with EG can give the best heat transfer performance of OHP. The previous research found that these alumina nanofluids were not beneficial in laminar or turbulent flow mode; they can enhance the heat transfer performance of an OHP.

Mousa [50] experimentally studied the effect of Al_2O_3–water based nanofluid concentration on the performance of a circular heat pipe. The operating parameters considered are working fluid filling ratio, volume fraction of nano-particle in the base fluid, and heat input. Thermal resistance decreases with increasing Al_2O_3–water based nanofluid compared to that of pure water. The results showed that the optimum filling ratio of charged fluid in heat pipe was about 0.45 to 0.50 for both pure water and Al_2O_3–water based nanofluid, respectively, and that the thermal performance of heat pipe can be decreased by increasing concentration of the nanofluid.



Dispal 23N4-80 (P1, Platelets, 9nm)

Dispal T25N4-80 (P2, Blades, 60nm)

Dispal X-0 (P3, Cylinders, 80nm)

Catapal-200 (P4, Bricks, 40nm)

Fig. 9. TEM images of alumina nanoparticles and photos of alumina nanofluids [49].

Do et al. [51] experimentally investigated the effect of nanofluids on the thermal performance of heat pipes by testing circular screen mesh wick heat pipes using water-based Al_2O_3 nanofluids with the volume fraction of 1.0 and 3.0 vol%. The wall temperature distributions and the thermal resistances between the evaporator and the adiabatic sections were measured and compared. The average evaporator wall temperatures of the heat pipes using Al_2O_3 nanofluids are much lower than that of DI water. The thermal resistance of the heat pipe using the water-based Al_2O_3 nanofluids with 3.0 volume percentage is significantly reduced by about 40% at the evaporator-adiabatic section. This experimental investigation concluded that the formation of coating layer at screen mesh wick of the evaporation region by Al_2O_3 nanoparticles (Fig. 10) is the principal reason for the thermal performance enhancement of the heat pipe using nanofluids because the layer can not only extend the evaporation surface with high heat transfer performance but also improve the surface wettability and capillary wicking performance.

Yang and Liu [52] have investigated the thermal performance of functionalized nanofluid (surface functionalized ordinary silica nanoparticles) and traditional nanofluid (water and same silica nanoparticles without functionalized) in a thermosyphon and observed that functionalized nanofluid can maintain long-term stability and without any sedimentation. Traditional nanofluids enhance the maximum heat flux. Further, it was found that both functionalized and traditional nanofluids have no effects on the condenser of the thermosyphon. Finally it can be concluded that there are no meaningful nanofluids effect on the thermal performance of thermosyphon.

The effect of input heat flow and fill ratio on the performance of the thermosyphon was investigated by Alizadehdakhel et al. [53]. The results showed that by increasing the inlet heat flow from 350 W to 500 W, the thermosyphon performance increases and higher energy decreases. The best performance of thermosyphon was obtained at the optimum fill ratio of 0.5 and using Fluent 6.2, UDF subroutine was developed to model phase change in thermosyphon and concluded that the complex heat and mass transfer can be successfully modeled using CFD technique.

Suresh et al. [54] have presented the heat transfer and pressure drop characteristics of Al_2O_3–Cu/water hybrid nanofluid with 0.1 vol% concentration through a uniformly heated circular tube, under constant heat flux boundary condition. The results showed that the enhancement of heat transfer performance by hybrid nanofluids is greater than that of pure water and also increase in Nusselt number of hybrid nanofluid is 10.94% more when compared to pure water. The convective heat transfer coefficient increases with an increase in Reynolds number. The hybrid nanofluid for laminar flow showed that maximum enhancement of 13.56% in Nusselt number at a Reynolds number of 1730 is possible when compared to pure water. The average increase in friction factor of 0.1% Al_2O_3–Cu/water hybrid nanofluid is 10.97% when compare to water. Further hybrid nanofluid will cause an extra penalty in the form of pumping power.

The surface temperature and vapor temperature of an air-cooled condenser heat pipe at steady and transient condition were determined by Arul and Velraj [55].The results showed that the performance of the condensing process is affected by the low surface convective heat transfer coefficient in the condenser and also suggested that to enhance the operation of heat pipe, the water cooled condenser can be used with a higher heat transfer coefficient and higher heat transfer can be obtained by addition of fins in the section.

The comparison of temperature distribution and the heat transfer rate of the thermosyphon heat pipe with iron-oxide nanofluid and DI water were studied experimentally by Huminic et al. [56]. Laser pyrolysis technique was used to obtain the iron oxide nanoparticles. The test was conducted for different concentrations like 0%, 2% and 5.3%.The addition of iron-oxide nano particles of 5.3% (by volume) in water improved the thermal performance compared to DI water. The study conducted that the heat transfer rate increases with increase in inclination of the heat pipe with nanoparticles, the thermal resistance decreases as the concentration increases and that the iron-oxide nanofluid has remarkable potential to improve the thermal performance of the thermosyphon heat pipe.

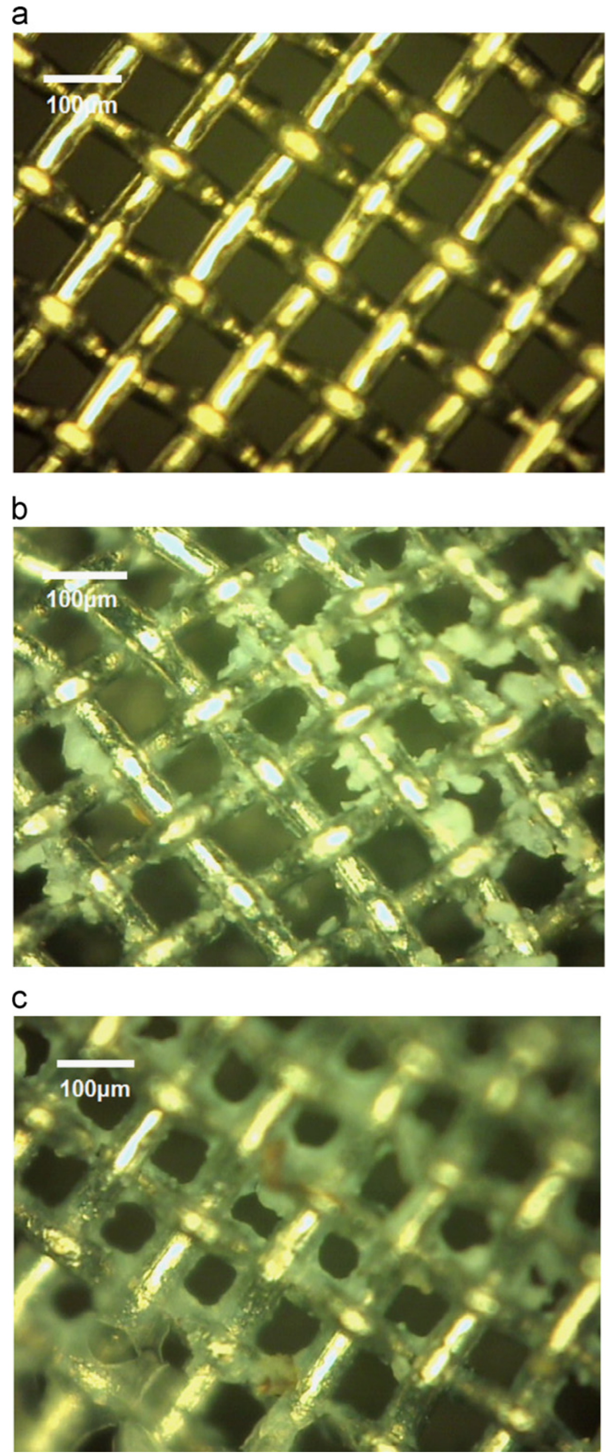


Fig. 10. Optical microscope images of a screen mesh wick surface (a) before experiment and (b) after experiment (1.0 vol%), (c) after experiment (3.0 vol%).[51].

Huminic and Huminic [57] presented the heat transfer characteristics of two-phase closed thermosyphon [TPCT] with iron-oxide nanofluids, focusing on heat transfer rate, evaporation and condensation heat transfer coefficient and thermal resistance. The TPCT is fabricated from a copper tube with outer diameter 15 mm and length 2000 mm and the mean diameter of iron oxide nanoparticles is 4–5 nm. It is attributed to the fact that the heat transfer rate increases with an increase in inclination angle by using nanofluids and also higher concentrations of iron oxide nanoparticles with pure water. The thermal resistance decreases with an increase in inclination angle and increases with an increase in volume concentration.

The Al_2O_3 nanoparticles shape effect on heat transfer performance in a oscillating heat pipe (OHP) was investigated experimentally by Yulong Ji et al. [58]. Four types of nanoparticles with the shapes of platelet, blade, cylinder and brick were studied. Final result shows that the mixture of ethylene glycol (EG) and cylinder like alumina nanoparticles achieve the best heat transfer, i.e., a performance enhancement efficiency of 75.8% with an operating temperature of 60 °C and volume fraction of 0.3% and also found that alumina nanofluids are not beneficial in laminar or turbulent flow mode and cannot enhance the heat transfer performance of OHP.

The fact that the heat pipes filled with self rewetting fluids have more stable, higher thermal efficiency and lower thermal resistance than heat pipe filled with water suggested by Senthilkumar et al. [59]. The results showed that aqueous solution of *n*-pentanol gives the better results than the aqueous solution of *n*-butanol. The reason is that the former has better surface-tension characteristics than the conventional fluid which has a negative surface-tension gradient and also showed that the suitability of self-rewetting fluids to improve the heat pipe performances.

Qu and Wu [60] experimentally investigated the different thermal performances of OHP's with SiO_2/water and Al_2O_3/water nanofluids. It is attributed to the fact that the alumina nanofluids – charged OHP existed an optimal concentration of 0.9 wt% at the overall thermal resistance and the evaporator wall temperature of about 0.057 °C/W and 5.6 °C, respectively, and also found that with silica nanofluids – charged OHP, the overall thermal resistance and the evaporator wall temperature increased with an increase in the mass concentration of silica nanoparticles. The deposition of alumina nanoparticles at the evaporator increases the surface nucleation sites and enhances the heat transfer of the OHP. The reverse effect is obtained for the silica nanoparticles.

The effect of concentration and type of nanofluids on the thermal performance of straight copper heat pipe has been experimentally investigated by Putra et al. [61]. It was found that Al_2O_3–water nanofluids with 5 vol% concentration gives better performance than water. Further, it was also found that the heat pipe formed coatings on the screen mesh surface, produced good capillary structures. Finally, the thermal performance of heat pipe increased with the nanofluids much greater than the conventional working fluids.

Liu and Li [62] summarized the recent researches on the effect of characteristics and mass concentrations of nanoparticles on the thermal performance of heat pipes. In this paper, the effect of different nanofluids on the thermal performance of different heat pipes like micro-grooved heat pipe, mesh wick heat pipe, sintered metal wick heat pipe, oscillating heat pipe and closed two-phase thermosyphon (gravity supported heat pipe) have been carried out. In miniature micro-grooved heat pipe, the effect of different nanoparticles size and nanoparticles concentration enhances the thermal performance of heat pipe. The boiling heat transfer may occur at high heat fluxes in heat pipes with micro grooves, but it cannot occur in the mesh and sintered metal heat pipes. In oscillating heat pipes, the temperature gradient makes a different volumetric distribution of the working fluid and causes pressure waves and fluid pulsations in each of the individual tube sections. In closed two-phase thermosyphon, the driving force of the fluid flow is the buoyancy generated by the boiling two-phase flow. They concluded that in majority of micro-grooved heat pipe, mesh wick heat pipe, oscillating heat pipe and most closed two-phase thermosyphon addition of nanoparticles to the working liquid significantly enhances the heat transfer, reduces the total heat resistance and increases maximum heat removal capacity. But still there are some problems and challenges on the mechanisms of the heat transfer enhancement. The present research of nanofluids in heat pipes is still at its initial stage and needs further development.

Solomon et al. [63] experimentally investigated the thermal performance of heat pipe operated with two different wicks (coated/uncoated). In this study, screen type wicks (100 mesh/inch) with and without deposition of nanoparticles were used. Copper particles with average particle size of 80–90 nm are coated over the surface of the screen mesh and simple immersion technique followed by drying is used. The heat pipes used had a length of 400 mm and diameter of 19.5 mm. In this study, Screen type wicks with and without deposition of nanoparticles were used. The wick structure of 4 layers of copper screen mesh with a size of 100 mesh/inch was used. The procedure for preparation of coated wick was repeated up to 6 times. The wick was kept inside the nano-fluid for 5 min and then the coated wick is exposed to hot air (at 80 °C) until it gets dry. By using scanning electron microscope (SEM), the wick structure was analyzed. After the 6th coating, an average pore size of 3–5 μm is seen in the SEM image. They observed that the thermal resistance of heat pipe at the evaporator section was reduced by around 40% due to the coated wick. The effect of coated wick reduces the wall temperature at the evaporator and condenser of the heat pipe. The reduction in the thermal resistance of the evaporator was higher than the increase in the thermal resistance of the condenser. Thermal resistance of the coated wick heat pipe was lower than that of conventional one. The author finally concluded that further research is still required in order to allow a complete characterization of the coated wick.

Yang and Liu [64] first carried out an experimental study on the flow boiling heat transfer of water based CuO nanofluids in thermosyphon loop. They studied a thermosyphon loop with the evaporator of rectangular chamber with a width of 100 mm, height of 100 mm and thickness of 10 mm. The condenser was made of a 16 mm OD copper tube with a length of 600 mm. The nanofluid consisted of CuO nanoparticles with an average diameter of 50 nm and DI water. The experimental data of the nanofluids were compared with those of DI water including the flow boiling characteristics of water and nanofluids in the evaporator. Experimental results showed that the flow boiling heat transfer in the evaporator of the thermosyphon loop can be enhanced by adding CuO nanoparticles into DI water. The maximum enhancement of the HTC obtained on an optimal mass concentration of 1.0 wt%. The CHF enhancement ratio of the nanofluid increases with increasing mass concentration of nanoparticles. The influence of pressure on the HTC enhancement has apparent and negligible effect on the CHF enhancement. The result showed that, the nanoparticles mass concentration and the boiling time both affects the surface morphology of the coating surface formed.

Saleh et al. [65] used a straight copper heat pipe with an outer diameter of 8 mm, an inner diameter of 7.44 mm and the length of 200 mm. A stainless steel wire screen mesh with a diameter of 56.5 μm and 67.42 strands per mm was used. ZnO nanofluids were prepared using a two-step procedure with base fluid ethylene glycol (EG). They mainly measured the temperature

distribution and thermal resistance of the heat pipe filled with pure EG and ZnO nanofluids at concentrations from 0.025 vol% to 0.5 vol%. The experimental data revealed that nanofluids containing a small fraction of nanoparticles had higher thermal conductivities compared to the base fluid. The conductivity ratio could be enhanced by approximately 5.3% until 15.5%. In addition, it was observed that the temperature distribution and the heat pipe thermal resistance were varied with the particle volume fraction and the size of the ZnO particles.

KeshavarzMoraveji and Razvarz [66] investigated the heat transfer characteristics of a sintered circular heat pipe with aluminum oxide nanofluids as the working fluid under different concentrations. The results were compared with those of the same heat pipe with distilled water as the working fluid. The heat pipe was made of a straight copper tube with an outer diameter and length of 6 mm and 190 mm, respectively. The spherical aluminum oxide nanoparticles of 35–45 nm with density 3.88 g/cm^3 were utilized. The experimental results confirmed that the use of aluminum oxide–water nanofluids in the heat pipe could enhance the thermal performance by reducing the thermal resistance and wall temperature difference.

Utomo et al. [67] experimentally and theoretically investigated the thermal conductivity, viscosity and heat transfer coefficient of water based alumina and titania nanofluids having spherical primary particles of 50–60 nm and 20–30 nm in diameters, respectively. An experimental set up consists of two horizontal, stainless steel test section of inner diameters 4.57 mm and 10 mm were used. The flow and heat transfer in nanofluid was numerically simulated using particle tracking model and modeling of the flow/heat transfer was done by using continua model. The results were found that smaller particle in titania nano fluids (20–30 nm) compared to alumina nanofluids (50–60 nm) may contribute to the lower effective thermal conductivity.

In this work, the relative viscosity of alumina nanofluid is slightly higher than that predicted by Einstein–Bachelor model. The authors concluded that relative viscosity of alumina and titania nano fluids were found to be higher than the prediction of Einstein–Bachelor model due to the formation of aggregates. Using 3-D numerical simulation, homogeneous flow model was used to predict macroscopic thermal behavior of nano fluids.

Kole and Dey [68] experimentally investigated the thermal performance of screen mesh wick heat pipes using water-based copper nano fluids. Copper nano particles (density: 8.94 g/cm^3) were purchased from Ms. Sigma-Aldrich (USA) of nominal diameter approximately 16 nm. In this study, no surfactant is added to the copper-distilled water nano fluids. The different concentrations of Cu nano particles like 0.0005 wt%, 0.005 wt%, 0.05 wt% and 0.5 wt% were prepared by using ultrasonicator followed by magnetic stirring process. The dimensions of heat pipe are length 300 mm, outer diameter 10 mm and wall thickness 0.6 mm and material used is copper. The evaporator section, adiabatic section and condenser section of the heat pipe are 70 mm, 80 mm and 150 mm, respectively. Thermal conductivity shows an enhancement of approximately 15% with 0.5 wt% loading of Cu nano particles. The results show that vertical heat pipes are found to perform better than other inclinations. Cu-distilled water nano fluid of 0.5 wt% reduced the thermal resistance by approximately 27%. Also observed that heat transfer enhancement achieved from the deposition of thin porous layer of nano particle in the evaporator region as shown in Fig.11. Further, the coated layer formed by the nano particles improves the surface wettability, reduces the contact angle, and increases the surface roughness and the wick's capillary action.

Li et al. [69] developed a mathematical model of evaporation and condensation heat transfer in copper water wicked heat pipe with a sintered grooved composite wick and compared with experiments. The author selected the composite wick rather than conventional wick in order to enhance the heat transfer. The heat pipe used in the study is 8 mm outer diameter copper heat pipe with a length of 300 mm. Fig. 12 shows SEM (scanning electron microscope) pictures of the composite wick without copper powder and with copper powder. The copper powder was sintered on the internal wall of a copper tube with 135 axial micro grooves under a fixed pressure in a 900°–1000 °C hydrogen atmosphere for 3 h. The cross-section of each groove had a height equal to 0.12 mm and width equal to 0.06 mm. The advantage of composite wick compared with traditional groove wick or sintered powder wick can provide an optimum combination of capillary pressure using the powder wick and permeability using axial grooves. A mathematical model was developed to find the macroscopic characteristics such as thermal resistance, temperature difference and heat transfer coefficients. The result showed that the working fluid is boiling at higher superheats and the equilibrium state was achieved by spending more time, because of the higher heat load. The trends of the evaporator thermal resistance are overlapped and the condenser thermal resistance increases at the beginning because heat pipe spends time to generate a stable liquid circulation. The total thermal resistance of heat pipe ranges from 0.02 K/W to 0.56 K/W.

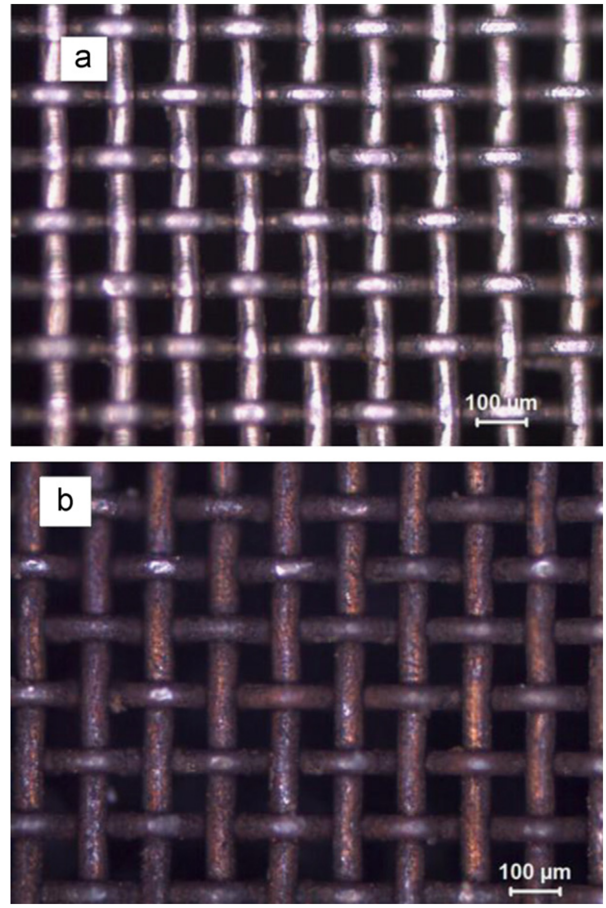


Fig. 11. Optical microscope images of a screen mesh wick surface (a) before experiment and (b) after experiment with 0.05 wt% Cu-distilled water nanofluid [68].

Senthilkumar et al. [70] have investigated experimentally to study the thermal efficiency enhancement of heat pipe using copper nano fluid. In this study, the average size of nano particle used was 40 nm and concentration of copper nano particle in the base fluid is 100 mg/l. The copper heat pipe of length 0.6 m, outer diameter 0.02 m and stainless steel wick material was used.

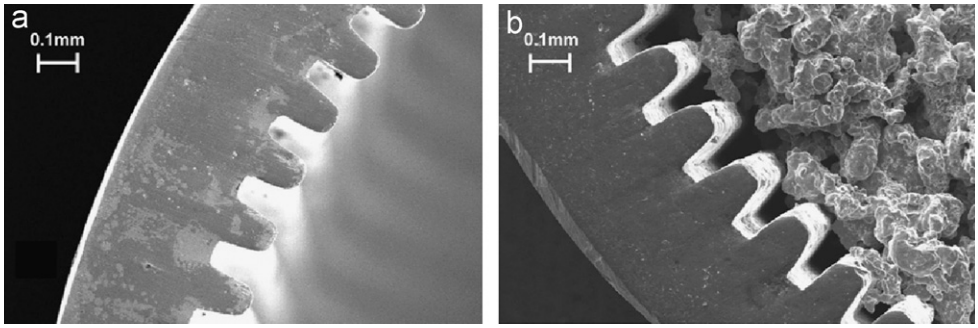


Fig. 12. SEM photographs of the sintered-grooved composite wick: (a) without copper powders sintered on, (b) with copper powders sintered on [69].

The experiment was conducted for different heat inputs (30, 40, 50, 60 and 70 W) and different inclination of pipe (0°, 15°, 30°, 45°, 60°, 75° and 90°). Finally concluded that the thermal efficiency of copper nano fluid was higher than the base fluid and thermal resistance was also considerably less than DI water.

3.1.1. Inferences from the experimental studies on the heat pipes with nanofluids

The comparison of various reports in the area of heat pipe with nanofluids were discussed in this paper. The results from the prior work done clearly showed that the enhancement of thermal efficiency of heat pipe differs greatly for different experiments due to different experimental conditions. There are still some problems and challenges on the mechanism of heat transfer enhancement not being clearly defined for the heat pipes using nanofluids. The present research of nanofluids in heat pipes are inadequate and needs further development.

3.2. Theoretical investigations

Shafahi et al. [71] numerically investigated the thermal performance of rectangular and disk-shaped heat pipes using nanofluids. The nanofluids such as Al_2O_3, CuO and TiO_2 with base fluid were considered. The operating parameters considered are the liquid pressure, liquid velocity profile, temperature distribution of the heat pipe wall, temperature gradient along the heat pipe. The performance parameters are thermal resistance and maximum heat load obtained for the flat-shaped heat pipes. The thermal performance of flat-shaped heat pipe using nanofluids is substantially enhanced compared with conventional fluid. The nanometer sized particles present in the working fluid results in a decrease in the thermal resistance and an increase in the maximum heat load capacity of the flat-shaped heat pipe. The existence of an optimum nanoparticles concentration level and wick thickness in maximizing the heat removal capability of the flat-shaped heat pipe was established. The presence of nanoparticles leads to a reduction in the speed of the liquid, smaller temperature difference along the heat pipe and the possibility of reduction in size under the same operational conditions.

Tahery et al. [72] analytically investigated the nanofluids with water base containing Al_2O_3 nanoparticles. The numerical works done for the cavity is differentially heated, both walls are isothermal and other two walls are adiabatic. The boundary conditions were on heated wall $U=V=0$, $\theta=1$, on cooled wall $U=V=0$, $\theta=0$ and on the adiabatic walls: $U=V=0$, $\delta\theta/\delta S=0$. For the numerical works, the nanofluids under natural convective heat transfer conditions were considered. The heating was done by two different ways: (i) The heater mounted to the down wall, (ii) It is mounted to the left vertical wall with a finite length. Simulation has been done for Al_2O_3 nanofluids with Newtonian behavior. Simulation has been carried out in the ranges $R_a=10^3$–10^6 and volumetric fraction of nanoparticles was 1.3%. The final findings showed that there is an increase in the average Nusselt number. This numerical investigation showed that the vertical cavities with nanofluids were better than horizontal cavities and had better efficiency in natural convection numerical modeling for both horizontal and vertical fluid layer. The results showed that the heat transfer behavior of nanofluids is very complex and many other important factors influence the heat transfer performance of nanofluids in natural convective heat transfer, which should be identified further in future works. Finally, concluded that further theoretical and experimental research investigations are needed to understand the heat transfer characteristics of nanofluids and identify new and unique applications for these fields.

Vasu et al. [73], theoretical analysis was carried with ε—NTU rating method by using $Al_2O_3+H_2O$ nanofluid as coolant on automobile flat tube plain fin compact heat exchanger. A detailed study of the parametric studies on compact heat exchanger is done by using ε—NTU numerical method and using $Al_2O_3+H_2O$ nanofluids a coolant. The factors considered for theoretical analysis were effect of air inlet temperature, effect of air and coolant mass flow rate, effect of coolant inlet temperature and effect of nanoparticles volume concentration. This paper concluded that the $Al_2O_3+H_2O$ nanofluid is compared with conventional fluids and observed that cooling capacity of $Al_2O_3+H_2O$ nanofluid is very high. The nanofluid's overall heat transfer coefficient is very high than water and decreases with increase in the volume fraction of nanoparticles.

Murugesan and Sivan [74], developed lower/upper limits for thermal conductivity of nanofluids and the theoretical datas are compared with the published experimental result. The comparison indicates that the experimental data considered lie between the newly developed limits and the present limits are more rigorous in placing a narrow lower and upper limit. This paper concluded that particle shape, Brownian motion and nanolayer are significant in enhancing the thermal conductivity of nanofluids. It will be possible to develop a more realistic theoretical model to predict the thermal conductivity of nanofluids, for better understanding of the role of these parameters.

Do and Pil Jang [75] numerically investigated the effect of water-based Al_2O_3 nanofluids as working fluid on the thermal performance of a flat micro-heat pipe with a rectangular grooved wick. The axial variations of the wall temperature, the evaporation and condensation rates are considered by solving the one dimensional conduction equation for the wall and the augmented Young–Laplace equation for the phase change process. The thermo physical properties of nanofluids as well as the surface characteristics formed by nanoparticles such as a thin porous coating are considered. The thin porous coating layer formed by nanoparticles suspended in nanofluids is a key effect of the heat transfer enhancement for the heat pipe using nanofluids.

The effects of the volume fraction and the size of nanoparticles on the thermal performance were studied and the results showed that the feasibility of enhancing the thermal performance up to 100% although water-based Al_2O_3 nanofluids with the concentration less than 1.0% is used as working fluid. Finally, it could be concluded that the thermal resistance of the nanofluid heat pipe tends to decrease with increasing the nanoparticles size compared with the previous experimental results.

Shafahi et al. [76] had studied (theoretically) the thermal performance of cylindrical heat pipe with Al_2O_3, CuO and TiO_2 by using two dimensional analyses. When using nanofluids, there is substantial change in the heat pipe thermal resistance, temperature distribution and maximum capillary heat transfer of the heat pipe was observed. By utilizing nanofluids resistance decreases as the concentration increases or as the particle diameter decreases for the smaller size of the cylindrical heat pipe. In this study, the influence of nanofluid and the geometrical characteristics of the wick on the maximum heat load carrying capability of the cylindrical heat pipe are investigated. The existence of an optimum mass concentration and smaller particle in size providing the highest thermal performance had been established.

3.2.1. Inferences from the theoretical studies on the heat pipes with nanofluids

The observations based on the reviewed literature on the heat pipes (Table 5) showed that the thermal performance of heat pipe using nanofluid is higher than that of the base fluid. A majority of the results that are available are of experimental findings and the theoretical investigations are limited. It is obvious that more research is needed in future in order to validate the simulation model with the experimental findings.

4. Conclusions

This paper presents an overview of the research results of heat transfer characteristics of heat pipes using nanofluids as working fluids. The results of open literature have shown that nanofluids have great potential of heat transfer in heat pipes and also the following conclusions can be drawn:

1. The nanoparticles present in the base fluid can significantly enhance the heat transfer, reduce the thermal resistance and increase the heat removal capacity.
2. The volume concentration and charge volume of nanoparticles increase the thermal efficiency and significantly reduce the thermal resistance of heat pipe when compared with base fluid.
3. The thermal performance of heat pipe will be enhanced by increasing the critical heat flux and convective heat transfer coefficient of nanofluid in base fluid.
4. The reasons for enhancement of the thermal performance of the FHP using the nanofluids are:
   a) The critical heat flux enhancement obtained due to higher wettability of nanofluids in heat pipes.
   b) The effective liquid conductance and the effective thermal conductivity of the wick structure in heat pipes is increased due to reduction in the boiling limit of nanofluids.
5. Hybrid nanofluids were not more effective compared with the pure nanoparticle nanofluid system.

Further theoretical and experimental investigations are needed to understand the heat transfer characteristics of nanofluids in heat pipes and to identify the new techniques to improve the heat transport properties of nanofluids in heat pipes.

References

[1] Wang X, Xu X, Choi SUS. Thermal conductivity of nanoparticle-fluid mixture. Journal of Thermo physics and Heat Transfer 1999;13:474–80.
[2] Yimin Xuan, Wilfried Roetzel. Conceptions for heat transfer correlation of nanofluids. International Journal of Heat and Mass Transfer 2000;43:3701–7.
[3] Wang BX, Li H, Peng XF. Research on the heat-conduction enhancement for liquid with nano-particle suspensions. Journal of Thermal Science 2002;11: 214–9.
[4] Yimin Xuan, Qiang Li. Heat transfer enhancement of nanofluids. International Journal of Heat and Fluid Flow 2000;21:58–64.
[5] Lin S, Kew PA, Cornwell K. Two-phase heat transfer to a refrigerant in a 1 mm diameter tube. International Journal of Refrigeration 2001;24:51–6.
[6] Lanchao Lin, Rengasamy Ponnappan, John Leland. High performance miniature heat pipe. International Journal of Heat and Mass Transfer 2002;45: 3131–42.
[7] Mehmet Esen. Thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants. Solar Energy 2004;76:751–7.
[8] Song F, Ewing D, Ching CY. Experimental investigation on the heat transfer characteristics of axial rotating heat pipes. International Journal of Heat and Mass Transfer 2004;47:4721–31.
[9] Yimin Xuan, Yuping Hong, Qiang Li. Investigation on transient behaviors of flat plate heat pipes. Experimental Thermal and Fluid Science 2004;28:249–55.
[10] Dongsheng Wen, Yulong Ding. Experimental investigation into convective heat transfer of nanofluids at the entrance region under laminar flow conditions. International Journal of Heat and Mass Transfer 2004;47:5181–8.
[11] Zhou DW. Heat transfer enhancement of copper nanofluid with acoustic cavitation. International Journal of Heat and Mass Transfer 2004;47: 3109–17.
[12] In Cheol Bang, Soon Heung Chang. Boiling heat transfer performance and phenomena of Al_2O_3–water nano-fluids from a plain surface in a pool. International Journal of Heat and Mass Transfer 2005;48:2407–19.
[13] Leonard L Vasiliev. Heat pipes in modern heat exchangers. Applied Thermal Engineering 2005;25:1–19.
[14] Vasiliev LL. Micro and miniature heat pipes—electronic component coolers. Applied Thermal Engineering 2008;28:266–73.
[15] Huang BJ, Lee JP, Chyng JP. Heat-pipe enhanced solar-assisted heat pump water heater. Solar Energy 2005;78:375–81.
[16] Huang BJ, Lee CP. Performance evaluation method of solar-assisted heat pump water heater. Applied Thermal Engineering 2007;27:568–75.
[17] Song Lin, Broadbent John, Ryan McGlen. Numerical study of heat pipe application in heat recovery systems. Applied Thermal Engineering 2005;25:127–33.
[18] Koo J, Kleinstreuer C. Laminar nanofluid flow in micro heat-sinks. International Journal of Heat and Mass Transfer 2005;48:2652–61.
[19] Min-Sheng Liu, Mark Ching-Cheng Lin, I-Te Huang, Chi-Chuan Wang. Enhancement of thermal conductivity with carbon nanotube for nanofluids. International Communications in Heat and Mass Transfer 2005;32:1202–10.
[20] Ying Yang George Zhang Z, Eric A Grulke, William B Anderson, Gefei Wu. Heat transfer properties of nanoparticle-in-fluid dispersions (nanofluids) in laminar flow. International Journal of Heat and Mass Transfer 2005;48:1107–16.
[21] Zeinali Heris S, SGh Etemad, Nasr Esfahany M. Experimental investigation of oxide nanofluids laminar flow convective heat transfer. International Communications in Heat and Mass Transfer 2006;33:529–35.
[22] Seok Pil Jang, Stephen USChoi. Cooling performance of a microchannel heat sink with nanofluids. Applied Thermal Engineering 2006;26:2457–63.
[23] Jinping Li, Deqing Liang, Kaihua Guo, Ruzhu Wang, Shuanshi Fan. Formation and dissociation of HFC134a gas hydrate in nano-copper suspension. Energy Conversion and Management 2006;47:201–10.
[24] Palm Samy Joseph, Roy Gilles, Nguyen Cong Tam. Heat transfer enhancement with the use of nanofluids in radial flow cooling systems considering temperature-dependent properties. Applied Thermal Engineering 2006;26: 2209–18.
[25] Shung-Wen Kang, Wei-Chang Wei, Sheng-Hong Tsai, Shih-Yu Yang. Experimental investigation of silver nanofluid on heat pipe thermal performance. Applied Thermal Engineering 2006;26:2377–82.
[26] Ding Yulong, Alias Hajar, Wen Dongsheng, Williams Richard A. Heat transfer of aqueous suspensions of carbon nanotubes (CNT nanofluids). International Journal of Heat and Mass Transfer 2006;49:240–50.
[27] Liu Di, Tang Guang-Fa, Zhao Fu-Yun, Wang Han-Qing. Modeling and experimental investigation of looped separate heat pipe as waste heat recovery facility. Applied Thermal Engineering 2006;26:2433–41.
[28] Vlassov Valeri V, de Sousa Fabiano L, Takahashi. Walter K. Comprehensive optimization of a heat pipe radiator assembly filled with ammonia or acetone. International Journal of Heat and Mass Transfer 2006;49:4584–95.
[29] He Yurong, Jin Yi, Chen Haisheng, Ding Yulong, Cang Daqiang, Lu Huilin. Heat transfer and flow behaviour of aqueous suspensions of TiO_2 nanoparticles (nanofluids) flowing upward through a vertical pipe. International Journal of Heat and Mass Transfer 2007;50:2272–81.
[30] Tam Nguyen Cong, Roy Gilles, Gauthier Christian, Galanis Nicolas. Heat transfer enhancement using Al_2O_3–water nanofluid for an electronic liquid cooling system. Applied Thermal Engineering 2007;27:1501–6.
[31] Trisaksri Visinee, Wongwises Somchai. Critical review of heat transfer characteristics of nanofluids. Renewable and Sustainable Energy Reviews 2007;11:512–23.

[32] Chein Reiyu, Chuang Jason. Experimental microchannel heat sink performance studies using nanofluids. International Journal of Thermal Sciences 2007;46:57–66.

[33] Ben Mansour Ridha, Galanis Nicolas, Tam Nguyen Cong. Effect of uncertainties in physical properties on forced convection heat transfer with nanofluids. Applied Thermal Engineering 2007;27:240–9.

[34] Wang Xiang-Qi, Mujumdar Arun S. Heat transfer characteristics of nanofluids: a review. International Journal of Thermal Sciences 2007;46:1–19.

[35] Gleiter M. Nanocrystalline materials. Progress in Materials Science 1989;33:223–315.

[36] Choi SUS, Eastman JA. Enhancing thermal conductivity of fluids with nanoparticles. In: Singer D A, Wang HP, editors. Developments and applications of non-Newtonian flows. New York: E-Publishing Inc; 1995. p. 99–105.

[37] Eastman JA, Choi SUS, Li S, Yu W, Thompson LJ. Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles. Applied Physics Letters 2001;78:718–20.

[38] Akoh Hiroshi, Tsukasaki Yukihiro, Yatsuya Shigeki, Tasaki Akira. Magnetic properties of ferromagnetic ultrafine particles prepared by vacuum evaporation on running oil substrate. Journal of Crystal Growth 1978;45:495–500.

[39] Hai-tao Zhu Yu-sheng, Lin Yan-sheng Yin. A novel one-step chemical method for preparation of copper nanofluids. Journal of Colloid and Interface Science 2004;277:100–3.

[40] Lo Chih-Hung, Tsung Tsing-Tshih, Chen Liang-Chia, Su Chun-His, Lin Hong-Ming. Fabrication of copper oxide nanofluid using submerged arc nanoparticle synthesis system (SANSS). Journal of Nanoparticle Research 2005;7:313–20.

[41] Lee S, Choi SUS, Li S, Eastman JA. Measuring thermal conductivity of fluids containing oxide nanoparticles. Journal of Heat Transfer 1999;121:280–9.

[42] Murshed SMS, Leong KC, Yang C. Enhanced thermal conductivity of TiO_2–water based nanofluids. International Journal of Thermal Sciences 2005;44:367–73.

[43] Hwang Y, Park HS, Lee JK, Jung WH. Thermal conductivity and lubrication characteristics of nanofluids. Current Applied Physics 2006;6:e67–71.

[44] Naphon Paisarn, Assadamongkol Pichai, Borirak Teerapong. Experimental investigation of titanium nanofluids on the heat pipe thermal efficiency. International Communications in Heat and Mass Transfer 2008;35:1316–9.

[45] Tsai CY, Chien HT, Ding PP, Chan B, Luh TY, Chen PH. Effect of structural character of gold nanoparticles in nanofluid on heat pipe thermal performance. Materials Letters 2004;58:1461–5.

[46] Chen Yu-Tang. Experimental study of silver nanofluids on flat heat pipe thermal performance. Journal of Marine Science and Technology 2010;18:731–4.

[47] Han WS, Rhi SH. Thermal characteristics of grooved heat pipe with hybrid nanofluids. Thermal Science 2011;15:195–206.

[48] Kang Shung-Wen, Wei Wei-Chiang, Tsai Sheng-Hong, Yang Shih-Yu. Experimental investigation of silver nano-fluid on heat pipe thermal performance. Applied Thermal Engineering 2006;26:2377–82.

[49] Ji Yulong, Wilson Corey, Chen Hsiu-hung, Ma Hongbin. Particle shape effect on heat transfer performance in an oscillating heat pipe. Nanoscale Research Letters 2011;6(1):296.

[50] Mousa MG. Effect of nanofluid concentration on the performance of circular heat pipe. Ain Shams Engineering Journal 2011;2:63–9.

[51] Do KyuHyung, Ha HyoJun, Pil Jang Seok. Thermal resistance of screen mesh wick heat pipes using the water-based Al_2O_3 nanofluids. International Journal of Heat and Mass Transfer 2010;53:5888–94.

[52] Yang Xue-Fei, Liu Zhen-Hua. Application of functionalized nanofluid in thermosyphon. Nanoscale Research Letters 2011;6(1):494.

[53] Alizadehdakhel Asghar, Rahimi Masoud, Alsairafi AmmarAbdulaziz. CFD modeling of flow and heat transfer in a thermosyphon. International Communications in Heat and Mass Transfer 2010;37:312–8.

[54] Suresh S, Venkitaraj KP, Selvakumar P, Chandrasekar M. Effect of Al_2O_3–Cu/water hybrid nanofluid in heat transfer. Experimental Thermal and Fluid Science 2012;38:54–60.

[55] Arul Selvan Annamalai, Velraj Ramalingam. Experimental investigation and CFD analysis of a air cooled condenser heat pipe. Thermal Science 2011;15:759–72.

[56] Huminic Gabriela, Huminic Angel, Morjan Ion, Dumitrache Florian. Experimental study of the thermal performance of thermosyphon heat pipe using iron oxide nanoparticles. International Journal of Heat and Mass Transfer 2011;54:656–61.

[57] Huminic Gabriela, Huminic Angel. Heat transfer characteristics of a two-phase closed thermosyphons using nanofluids. Experimental Thermal and Fluid Science 2011;35:550–7.

[58] Ji Yulong, Ma Hongbin, Su Fengmin, Wang Guoyou. Particle size effect on heat transfer performance in an oscillating heat pipe. Experimental Thermal and Fluid Science 2011;35:724–7.

[59] Rathinasamy Senthilkumar, Subaiah Vaidyanathan, Sivaramanb Balasubramanian. Thermal analysis of heat pipe using self rewetting fluids. Thermal Science 2011;15:879–88.

[60] Qu Jian, Wu Huiying. Thermal performance comparison of oscillating heat pipes with SiO_2/water and Al_2O_3/water nanofluids. International Journal of Thermal Sciences 2011;50:1954–62.

[61] Putra Nandy, Septiadi WayanNata, Rahman Haolia, Irwansyah Ridho. Thermal performance of screen mesh wick heat pipes with nanofluids. Experimental Thermal and Fluid Science 2012;40:10–7.

[62] Liu Zhen-Hua, Li Yuan-Yang. A new frontier of nanofluid research—application of nanofluids in heat pipes. International Journal of Heat and Mass Transfer 2012;55:6786–97.

[63] Brusly Solomon A, Ramachandran K, Pillai BC. Thermal performance of a heat pipe with nanoparticles coated wick. Applied Thermal Engineering 2012;36:106–12.

[64] Xue-Fei Yang Zhen-Hua Liu. Flow boiling heat transfer in the evaporator of a loop thermosyphon operating with CuO based aqueous nanofluid. International Journal of Heat and Mass Transfer 2012;55:7375–84.

[65] Saleh Rosari, Putra Nandy, Prakoso SuhendroPurbo, Septiadi WayanNata. Experimental investigation of thermal conductivity and heat pipe thermal performance of ZnO nanofluids. International Journal of Thermal Sciences 2013;63:125–32.

[66] KeshavarzMoraveji Mostafa, Razvarz Sina. Experimental investigation of aluminum oxide nanofluid on heat pipe thermal performance. International Communications in Heat and Mass Transfer 2012;39:1444–8.

[67] Utomo AdiT, Poth Heiko, Robbins Phillip T, Pacek AndrzejW. Experimental and theoretical studies of thermal conductivity, viscosity and heat transfer coefficient of titania and alumina nanofluids. International Journal of Heat and Mass Transfer 2012;55:7772–81.

[68] Kole Madhusree, Dey TK. Thermal performance of screen mesh wick heat pipes using water-based copper nanofluids. Applied Thermal Engineering 2013;50:763–70.

[69] Li Yong, He Heng-fei, Zeng Zhi-xin. Evaporation and condensation heat transfer in a heat pipe with a sintered-grooved composite wick. Applied Thermal Engineering 2013;50:342–51.

[70] Senthilkumar R, Vaidyanathan S, Sivaraman B. Effect of inclination angle in heat pipe performance using copper nanofluid. Procedia Engineering 2012;38:3715–21.

[71] Shafahi Maryam, Bianco Vincenzo, Vafai Kambiz, Manca Oronzio. Thermal performance of flat-shaped heat pipes using nanofluids. International Journal of Heat and Mass Transfer 2010;53:1438–45.

[72] Tahery AA, Pesteei SM, Zehforoosh A. Numerical study of heat transfer performance of homogenous nanofluids under natural convection. International Journal of Chemical Engineering and Applications 2010;1:49–54.

[73] Vasu V, Rama Krishna K, ACS Kumar. Application of nanofluids in thermal design of compact heat exchanger. International Journal of Nanotechnology and Applications 2008;2:75–87.

[74] Chandrasekhar Murugesan, Suresh Sivan. Limits for thermal conductivity of nanofluids. Thermal Science 2010;14:65–71.

[75] Hyung Do Kyu, Pil Jang Seok. Effect of nanofluids on the thermal performance of a flat micro heat pipe with a rectangular grooved wick. International Journal of Heat and Mass transfer 2010;53:2183–92.

[76] Maryam Shafahi Vincenzo, Bianco Kambiz, Vafai Oronzio Manca. An investigation of the thermal performance of cylindrical heat pipes using nanofluids. International Journal of Heat and Mass Transfer 2010;53:376–83.